Year: 2015

Complex osteotomies of tibial plateau mal-unions using computer-assisted planning and patient-specific surgical guides: Preliminary report of three cases

Fürnstahl, Philipp ; Vlachopoulos, Lazaros ; Schweizer, Andreas ; Fucentese, Sandro F ; Koch, Peter P

Abstract: The accurate reduction of tibial plateau malunions can be challenging without guidance. In this work, we report on a novel technique that combines 3D computer-assisted planning with patient-specific surgical guides for improving reliability and accuracy of complex intra-articular corrective osteotomies. Preoperative planning based on 3D bone models was performed to simulate fragment mobilization and reduction in three cases. Surgical implementation of the preoperative plan using patient-specific cutting and reduction guides were evaluated, benefits and limitations of the approach were identified and discussed. The preliminary results are encouraging and show that complex intra-articular corrective osteotomies can be accurately performed with this technique. For selective patients with complex mal-unions around the tibia plateau this method might be an attractive option, with the potential to facilitate the most accurate correction possible.

DOI: https://doi.org/10.1097/BOT.0000000000000301

Originally published at:
Fürnstahl, Philipp; Vlachopoulos, Lazaros; Schweizer, Andreas; Fucentese, Sandro F; Koch, Peter P (2015). Complex osteotomies of tibial plateau mal-unions using computer-assisted planning and patient-specific surgical guides: Preliminary report of three cases. Journal of Orthopaedic Trauma, 29(8):e270-e276.
DOI: https://doi.org/10.1097/BOT.0000000000000301

Journal of Orthopaedic Trauma Publish Ahead of Print
DOI: 10.1097/BOT.0000000000000301

Complex osteotomies of tibial plateau mal-unions using computer-assisted planning and patient-specific surgical guides: Preliminary report of three cases

*Philipp Fürnstahl, PhD, *Lazaros Vlachopoulos, MD, **Andreas Schweizer, MD **Sandro F Fucentese, MD, **Peter P Koch, MD

*Computer-Assisted Research and Development Group, Balgrist University Hospital, University of Zurich, Forchstrasse 340, CH-8008 Zurich, Switzerland

**Orthopedic Department, Balgrist University Hospital,
University of Zurich, Forchstrasse 340, CH-8008 Zurich, Switzerland

<u>Corresponding author:</u>

Philipp Fürnstahl, PhD
Computer-Assisted Research and Development Group,
Balgrist University Hospital, Forchstrasse 340, CH-8008 Zurich
Phone: 0041 44 386 1111, Fax: 0041 44 386 1109
Email: philipp.fuernstahl@card.balgrist.ch

All authors declare that they have no conflict of interest.

SUMMARY

The accurate reduction of tibial plateau malunions can be challenging without guidance. In this work, we report on a novel technique that combines 3D computer-assisted planning with patient-specific surgical guides for improving reliability and accuracy of complex intra-articular corrective osteotomies. Preoperative planning based on 3D bone models was performed to simulate fragment mobilization and reduction in three cases. Surgical implementation of the preoperative plan using patient-specific cutting and reduction guides were evaluated, benefits and limitations of the approach were identified and discussed. The preliminary results are encouraging and show that complex intra-articular corrective osteotomies can be accurately performed with this technique. For selective patients with complex mal-unions around the tibia plateau this method might be an attractive option, with the potential to facilitate the most accurate correction possible.

Keywords

Osteotomy – patient-specific – surgical guide – mal-union – tibia plateau fracture – knee

INTRODUCTION

The knee joint is one of the most critical weight-bearing regions in the lower extremity. As a consequence, fractures around the tibia plateau may significantly affect articular loading, stability and even range of motion (ROM). The primary goal in treatment is anatomical reconstruction of the articular surface and the mechanical axis, aiming to restore function of the knee joint. Fractures can be treated conservatively for minimally displaced fragments, otherwise surgical management is recommended [1-3]. Well-established surgical techniques like open reduction and internal fixation (ORIF), external fixation, or arthroscopically assisted osteosynthesis can be chosen for this purpose [2,4-13]. However, operative management is challenging [14] and may be associated with mal-union if reduction is imprecise [3,15-17]. Mal-union can result in posttraumatic osteoarthritis and loss of function. Ultimately, salvage procedures such as total knee arthroplasty (TKA) or rarely knee arthrodesis may be necessary in an end stage situation [17].

An intra-articular corrective osteotomy, although being a complex intervention, may be a preferable treatment option for posttraumatic mal-unions [15,18]. In this procedure, the mal-united fragment is osteotomized and reduced to its anatomically correct position according to a preoperative plan. However, exact quantification of intra-articular mal-unions is difficult with traditional imaging techniques due to the three-dimensional (3D) nature of the deformity. It is even more challenging to exactly reproduce the preoperative objective during surgery. Although computer-assisted planning and guidance techniques are commonly used to support surgeons in performing TKA and high tibia osteotomies, the surgical correction of intra-articular posttraumatic mal-unions with such methods was so far not addressed. Oka et al. [19]

and Schweizer et al. [20] demonstrated the feasibility of combining 3D computer-assisted planning with patient-specific guides for correcting complex intra-articular mal-unions of the distal radius. In their method, a 3D preoperative plan was created that relied on the mirrored contralateral extremity. Based on this plan, individualized rapid-prototyped guides were manufactured to precisely reproduce reduction in the surgery.

We have extended the surgical technique proposed by Schweizer et al. [20] and report on our early experiences in operative treatment of posttraumatic intra-articular mal-unions of the proximal tibia.

PREOPERATIVE PLANNING AND SURGICAL TECHNIQUE

The proposed approach relies on computer-assisted preoperative planning to quantify a malunion and the required reduction in 3D. As the contralateral tibia will be used as a 3D reconstruction template, it is required that the contralateral limb of the patient is asymptomatic without previous history of trauma or obvious malalignment. In a first step, 3D triangular surface models of the pathological and contralateral normal tibia are generated. The bone models are extracted from computed tomography (CT) scans semi-automatically using the segmentation functionality of the Mimics software (Materialise, Loewen, Belgium): Intensity thresholding and region growing is applied for identifying the cortical bone layer and for separating the tibia from surrounding bone anatomy, respectively.

Computer-assisted preoperative planning is performed on a standard personal computer using a custom-made software application CASPA (University Hospital Balgrist, Zurich, Switzerland) . The 3D model of the contralateral tibia is mirrored and subsequently aligned to the pathological model using a surface registration algorithm. As in similar approaches [21], the iterative closest point method [22] (ICP) is used to superimpose the undeformed regions of the bone surfaces (i.e., the epiphyseal and meta/diaphyseal parts) in an automatic fashion by minimizing the quadratic distances between surface points.

Next, the fracture lines and articular step-off have to be assessed to create the osteotomy plane(s). Dependent on the pathology either a single or a combination of multiple osteotomy planes (i.e., curved cut) is required for mobilizing the fragment that must be reduced. After virtual mobilization, the anatomical correct position of the fragment was determined by aligning it to the reconstruction template. By doing so, the required reduction can be exactly quantified in 3D (i.e., 3 degrees-of-freedom in translation and 3 degrees-of-freedom in rotation) as the relative transformation of the fragment in its initial and reduced configuration. However, applying the so-obtained 3D measurements in the surgery to correct intra-articular malunion can be challenging [20].

One possibility to facilitate this task is the use of patient-specific guides. The basic idea of such an approach is that a guide body is molded on the bone surface. The irregular bone surface around the osteotomy helps to uniquely identify the location on the bone where the guide has to be positioned. We have developed different guides for supporting cutting and reduction.

Dependent on the complexity of the osteotomy, two different types of cutting guides are applied. If only one planar cut is required, parallel K-wires (2 mm diameter) are used to intraoperatively define the osteotomy plane. Preoperatively, virtual K-wires, represented by cylinders, are aligned on the osteotomy plane in the planning application (Figure 1 a). Based on the cylinders, a guide (*cutting guide type I*) with drill sleeves is designed in order to exactly set the K-wires on their planned position in the surgery (Figure 1 b). The osteotomy is subsequently performed by guiding the saw blade along the K-wires (Figure 1 c). A different technique [20] is applied for performing curved cuts: As depicted in Figure 2, the basic idea of this approach is that the cut is coarsely defined by consecutively drilling holes that are spaced between 5 mm to 10 mm. The position and direction is defined by drill sleeves that are integrated in a guide (*cutting guide type II*). Afterwards, the holes are connected with a cannulated chisel to complete the osteotomy.

In a similar fashion K-wires are combined with guides to reproduce the 3D-planned reduction in the surgery. The general procedure for creating a reduction guide is illustrated in Figure 3. First, cylinders representing 2 mm K-wires are created in the planning application (Figure 3 a). The cylinders are virtually fixed to the proximal and distal fragments. The corresponding drill sleeves to set the K-wires in the surgery are typically integrated into a cutting guide (Figure 3 b). A separate reduction guide is created based on the position and orientation of the cylinders after simulated reduction (Figure 3 c). It must be noted that such a guide must consist of two pluggable parts because the K-wires are divergent after reduction. After the osteotomy, the proximal and distal parts of the guide are slid along the K-wires (Figure 3 d). Thereafter, the parts are stably connected with a clicking mechanism to push the fragment to its anatomical correct position (Figure 3 e). After temporary fragment fixation using an additional K-wire, each part of the guide is separately removed, followed by fragment fixation with an osteosynthesis plate.

Based on the guide models provided as STL files, the guides used in the presented cases were produced by Medacta International S.A. (Castel San Pietro, Switzerland) with a selective laser sintering technique based on polyamide PA-12. Sterilization was performed with conventional steam pressure at 130º C. It had been validated in laboratory experiments that no shrinkage can occur at this temperature.

PATIENTS AND RESULTS

The proposed surgical technique was applied to three cases, characterized by an increasing level of complexity. Informed consent was obtained from all patients preoperatively regarding permission to report on their medical history and postoperative results. For each patient, preoperative assessment comprised a long leg X-ray and bilateral CT scans (120 kV; axial resolution: 1 mm; Philips Brilliance 40 CT, Philips Healthcare, Best, The Netherlands) of the pathological and the contralateral (normal) tibia. In all cases a multiplanar mal-union was confirmed by the 3D analysis (see Table, Supplemental Digital Content 1). The overall preoperative planning time including guide design was between two and four hours, depending on the case.

In case 1, a 32-year-old mason had sustained a bicondylar fracture (Schatzker type V, AO/OTA Classification [23] 41-C3) of the left tibial plateau that was conservatively treated (Figure 4). The lateral tibial plateau healed in anatomical position whereas the medial part dislocated progressively (Figure 5 a), resulting in a mal-union and anteromedial pain. The patient was referred to our hospital considering corrective osteotomy nine months after trauma. Physical examination revealed unrestricted ROM, tenderness at the medial joint line, and effusion. The knee was ligamentous stable. Surgery was performed eleven months after trauma with an anteromedial approach. The pes anserinus was only released in the proximal part. The superficial part of the medial collateral ligament was slightly detached anteriorly. An incomplete subchondral osteotomy was performed using a cutting guide (*type I*) and a surgical saw, followed by anatomical reduction which was guided as well.

In case 2, a 42-year-old painter sustained a multifragmentary fracture of the left tibia with a multi-part fracture of the eminentia intercondylaris (Schatzker type II, AO/OTA Classification [23] 41-B3), treated by ORIF in a trauma center. However, the patient was never pain free and was referred to our clinic six years later. Clinically, the medial compartment was still unremarkable with a negative varus stress test while the patient experienced pain with a substantial subluxation in the posterolateral defect of the tibia plateau during flexion. Effusion did occur but the knee was ligamentous stable and had unrestricted ROM. The 3D comparison with the contralateral tibia revealed a depression in the dorsal half of the lateral tibia plateau (see Table, Supplemental Digital Content 1; Figure 5 a). Four months after consultation, surgery was performed extending the former lateral approach. The posterior part of the tractus iliotibialis was released to expose the tuberculum Gerdy which was used as a landmark for the guides. For better visualization of the posterior part of the joint, an osteotomy of the lateral femoral condyle was performed. Next, a cutting guide (*type I*) was applied and a first cut was performed from anterior with a surgical saw. Thereafter, the bone was accessed from the lateral side above the proximal tibiofibular joint to completely mobilize the fragment with using two additional cutting guides (*type II*) and a chisel.

In case 3, a 29-year-old engineer had a skiing accident, resulting in a split depression fracture of the left lateral tibia plateau (Schatzker type II, AO/OTA [23] Classification 41-B3). The fracture was treated with ORIF in another institution. Sixteen months after trauma, the patient had a consultation in our hospital due to persistent pain and considerable functional impairment. Evaluation showed a mal-union of the biggest lateral fragment (see Table, Supplemental Digital Content 1; Figure 5 a) with already degenerative changes of the surrounding cartilage. Due to the young age of the patient, a corrective osteotomy was our preferable surgical treatment. Surgery was performed 22 months after trauma. The bone was accessed from anterolateral and soft tissue was removed from the lateral tibial head. Two cutting guide (*type II*) were applied in combination with a cannulated chisel. One guide was used to mobilize the fragment as planned and one was required to remove an additional bone wedge. Thereafter, the two-part reduction guide permitted correction of the multi-planar deformity.

In all cases, the fit of the guides appeared to be stable and well-defined. The postoperative course was uneventful. Radiological examination showed that all osteotomies healed in between three and six months after surgery. The minimum follow up time was between 12-14 months. A quantitative evaluation of the reduction error based on postoperative CT is given in Table, Supplemental Digital Content 1. The residual error was assessed by comparing the preoperative planning result with the 3D model of the postoperative tibia (Figure 5 b). In case 1 and 3 no limitation of the ROM was observed and there was no evidence of effusion. These two patients were very satisfied with the outcome and continued their former job (case 3) or pursued another job (case 1). In case 2, the osteotomy was not entirely performed as planned, because the fragment could not be mobilized completely to achieve the planned position. However, failure to mobilize the fragment was not a failure of the system but of the execution of the procedure. Reason for the incomplete mobilization was missing guidance of the chisel in the medial part. Six months postoperatively, this patient improved in terms of posterolateral pain and subluxation but medial pain increased slightly due to the underlying varus osteoarthritis. ROM was not limited but effusion was still present. The patient was not able to continue his former job, primarily caused by pain in the (untreated) medial part of the knee.

DISCUSSION

In this report we described a novel technique for performing complex intra-articular corrective osteotomies using 3D computer-assisted planning combined with patient-specific surgical guides.

Surgical treatment of tibial plateau fractures remains challenging [24] and may be associated with severe complication such as mal-union or post-traumatic gonarthrosis [3,25]. Therefore, a corrective osteotomy may be indicated in young adults to decrease risk of gonarthrosis [3,8,26]. Several studies [3,15,27,28] emphasized the importance of preoperative planning for exact quantification of mal-unions. Several authors proposed to use 3D-reconstructed CT to improve assessment of the deformity [15,26,29], although still relying on preoperative planning based on 2D radiographs. Mast et al. [27] was one of the first reporting on the use of the contralateral healthy tibia as a 2D reconstruction template for unilateral shaft mal-unions. More recently, 3D surface models of the contralateral bone have been used as reconstruction templates for the preoperative planning of corrective shaft osteotomies of the lower extremities [30] as well as for extra-articular [31-33] and intra-articular [19,20] osteotomies of the upper extremities. In these studies, patient-specific guides were applied to accurately reproduce preoperative planning during surgery. Guides or navigation systems were also used in other types of interventions around the knee to support the surgeon in performing tibial plateau fracture reduction [34], high tibia osteotomies [35-42] or TKA [43,44].

We presented a computer-assisted surgical technique that has been initially applied to the distal radius articulation [20]. The proposed approach permitted accurate multi-planar reduction of 3D deformities. Moreover, it was even possible to perform complex, curved cuts: In cases 2 and 3, a multi-planar closing wedge osteotomy was performed which required preoperatively calculating the exact 3D shape of the wedge to be removed. For completion of such types of osteotomies, the use of a cannulated chisel is suggested to prevent technical errors, which may lead to an incomplete mobilization of the fragment, as observed in case 2. In this case, not even the reduction of the mobilized part was satisfactory (i.e., above 4º residual error), since the repositioning relied only on manual alignment of congruent osteotomy surfaces. Therefore, we have further developed the design of the intra-articular guides combining the cutting guides with reduction guides, as demonstrated for cases 1 and 3. In these patients, the accuracy of the reduction was within 1 mm and 1.8º. These results are promising compared to other studies, which either were more inaccurate [20] or had similar accuracy under laboratory conditions [45].

The study and its proposed surgical technique had several limitations. First, the method was only applied to a small number of patients. Clinical scores were not evaluated, since a focus was laid on first describing the surgical technique and measuring its accuracy. As the type of procedure may always remain very selective, being only feasible for a few qualifying patients, it was important for us to report first experiences to the community. This may help assessing advantages and drawbacks of this technology and to decide whether it would be worthwhile to pursue further development. Moreover, an additional CT is required if the contralateral side should be used as a reconstruction template, resulting in increased radiation exposure. On the contrary, the technique may reduce total fluoroscopy time during surgery. Lastly, additional expenses of approximately €250 (USD 340) per case arise due to guide manufacturing.

In conclusion, the presented technique enabled us to perform complex intra-articular osteotomies in a controlled fashion, restoring congruity of the knee joint. For selective patients with mal-unions around the tibia plateau this method might be an attractive option, with the potential to facilitate the most accurate correction possible. High accuracy was demonstrated in two of three cases. However, benefits must be confirmed in a prospective clinical study with a larger number of cases and outcome evaluation.

REFERENCES

1. Schatzker J, McBroom R, Bruce D. The tibial plateau fracture. The Toronto experience 1968-1975. Clin Orthop Relat Res 1979:94-104.

2. Holzach P, Matter P, Minter J. Arthroscopically assisted treatment of lateral tibial plateau fractures in skiers: use of a cannulated reduction system. J Orthop Trauma 1994;8:273-81.

3. Papagelopoulos PJ, Partsinevelos AA, Themistocleous GS, et al. Complications after tibia plateau fracture surgery. Injury 2006;37:475-84.

4. Berkson EM, Virkus WW. High-energy tibial plateau fractures. J Am Acad Orthop Surg 2006;14:20-31.

5. Chiu CH, Cheng CY, Tsai MC, et al. Arthroscopy-assisted reduction of posteromedial tibial plateau fractures with buttress plate and cannulated screw construct. Arthroscopy 2013;29:1346-54.

6. Dall'oca C, Maluta T, Lavini F, et al. Tibial plateau fractures: compared outcomes between ARIF and ORIF. Strategies Trauma Limb Reconstr 2012;7:163-75.

7. Hung SS, Chao EK, Chan YS, et al. Arthroscopically assisted osteosynthesis for tibial plateau fractures. J Trauma 2003;54:356-63.

8. Lustig S, Khiami F, Boyer P, et al. Post-traumatic knee osteoarthritis treated by osteotomy only. Orthop Traumatol Surg Res 2010;96:856-60.

9. Manidakis N, Dosani A, Dimitriou R, et al. Tibial plateau fractures: functional outcome and incidence of osteoarthritis in 125 cases. Int Orthop 2010;34:565-70.

10. Musahl V, Tarkin I, Kobbe P, et al. New trends and techniques in open reduction and internal fixation of fractures of the tibial plateau. J Bone Joint Surg Br 2009;91:426-33.

11. Rademakers MV, Kerkhoffs GM, Sierevelt IN, et al. Operative treatment of 109 tibial plateau fractures: five- to 27-year follow-up results. J Orthop Trauma 2007;21:5-10.

12. Ramos T, Ekholm C, Eriksson BI, et al. The Ilizarov external fixator--a useful alternative for the treatment of proximal tibial fractures. A prospective observational study of 30 consecutive patients. BMC Musculoskelet Disord 2013;14:11.

13. Stevens DG, Beharry R, McKee MD, et al. The long-term functional outcome of operatively treated tibial plateau fractures. J Orthop Trauma 2001;15:312-20.

14. Volpin G, Dowd GS, Stein H, et al. Degenerative arthritis after intra-articular fractures of the knee. Long-term results. J Bone Joint Surg Br 1990;72:634-8.

15. Paley D. Intra-Articular Osteotomies of the Hip, Knee, and Ankle. Operative Techniques in Orthopaedics 2011;21:184-96.

16. Kettelkamp DB, Hillberry BM, Murrish DE, et al. Degenerative arthritis of the knee secondary to fracture malunion. Clin Orthop Relat Res 1988:159-69.

17. Parratte S, Boyer P, Piriou P, et al. Total knee replacement following intra-articular malunion. Orthop Traumatol Surg Res 2011;97:S118-23.

18. Kerkhoffs GM, Rademakers MV, Altena M, et al. Combined intra-articular and varus opening wedge osteotomy for lateral depression and valgus malunion of the proximal part of the tibia. Surgical technique. J Bone Joint Surg Am 2009;91 Suppl 2 Pt 1:101-15.

19. Oka K, Moritomo H, Goto A, et al. Corrective osteotomy for malunited intra-articular fracture of the distal radius using a custom-made surgical guide based on three-dimensional computer simulation: case report. J Hand Surg Am 2008;33:835-40.

20. Schweizer A, Furnstahl P, Nagy L. Three-dimensional correction of distal radius intra-articular malunions using patient-specific drill guides. J Hand Surg Am 2013;38:2339-47.

21. Schweizer A, Furnstahl P, Harders M, et al. Complex radius shaft malunion: osteotomy with computer-assisted planning. Hand (N Y) 2010;5:171-8.

22. Besl PJ, McKay ND. A method for registration of 3-D shapes. Pattern Analysis and Machine Intelligence, IEEE Transactions on 1992;14:239-56.

23. Marsh JL, Slongo TF, Agel J, et al. Fracture and dislocation classification compendium - 2007: Orthopaedic Trauma Association classification, database and outcomes committee. J Orthop Trauma 2007;21:S1-133.

24. Saengnipanthkul S. Uni-condyle high tibial osteotomy for malunion of medial plateau fracture: surgical technique and case report. J Med Assoc Thai 2012;95:1619-24.

25. Honkonen SE. Degenerative arthritis after tibial plateau fractures. J Orthop Trauma 1995;9:273-7.

26. Krettek C, Hawi N, Jagodzinski M. Intracondylar segment osteotomy: correction of intra-articular malalignment after fracture of the tibial plateau. Unfallchirurg 2013;116:413-26.

27. Mast JW. Preoperative planning in the surgical correction of tibial nonunions and malunions. Clin Orthop Relat Res 1983:26-30.

28. Paley D, Chaudray M, Pirone AM, et al. Treatment of malunions and mal-nonunions of the femur and tibia by detailed preoperative planning and the Ilizarov techniques. Orthop Clin North Am 1990;21:667-91.

29. Pilson HT, Reddix RN, Jr., Mutty CE, et al. The long lost art of preoperative planning--resurrected? Orthopedics 2008;31.

30. Victor J, Premanathan A. Virtual 3D planning and patient specific surgical guides for osteotomies around the knee: a feasibility and proof-of-concept study. Bone Joint J 2013;95-B:153-8.

31. Miyake J, Murase T, Oka K, et al. Computer-assisted corrective osteotomy for malunited diaphyseal forearm fractures. J Bone Joint Surg Am 2012;94:e150.

32. Schweizer A, Furnstahl P, Nagy L. Three-dimensional computed tomographic analysis of 11 scaphoid waist nonunions. J Hand Surg Am 2012;37:1151-8.

33. Takeyasu Y, Oka K, Miyake J, et al. Preoperative, computer simulation-based, three-dimensional corrective osteotomy for cubitus varus deformity with use of a custom-designed surgical device. J Bone Joint Surg Am 2013;95:e1731-9.

34. Oberst M, Hauschild O, Konstantinidis L, et al. Effects of three-dimensional navigation on intraoperative management and early postoperative outcome after open reduction and internal fixation of displaced acetabular fractures. J Trauma Acute Care Surg 2012;73:950-6.

35. Kyung BS, Kim JG, Jang KM, et al. Are navigation systems accurate enough to predict the correction angle during high tibial osteotomy?: comparison of navigation systems with 3-dimensional computed tomography and standing radiographs. Am J Sports Med 2013;41:2368-74.

36. Okal F, Hart R, Komzak M, et al. Computer-assisted kinematic 2D and 3D navigation in medial opening-wedge high-tibial valgus osteotomy. Acta Chir Orthop Traumatol Cech 2013;80:159-64.

37. Reising K, Strohm PC, Hauschild O, et al. Computer-assisted navigation for the intraoperative assessment of lower limb alignment in high tibial osteotomy can avoid outliers compared with the conventional technique. Knee Surg Sports Traumatol Arthrosc 2013;21:181-8.

38. Keppler P, Gebhard F, Grutzner PA, et al. Computer aided high tibial open wedge osteotomy. Injury 2004;35 Suppl 1:S-A68-78.

39. Wang G, Zheng G, Keppler P, et al. Implementation, accuracy evaluation, and preliminary clinical trial of a CT-free navigation system for high tibial opening wedge osteotomy. Comput Aided Surg 2005;10:73-85.

40. Bae DK, Song SJ, Yoon KH. Closed-wedge high tibial osteotomy using computer-assisted surgery compared to the conventional technique. J Bone Joint Surg Br 2009;91:1164-71.

41. Ellis RE, Tso CY, Rudan JF, et al. A surgical planning and guidance system for high tibial osteotomy. Comput Aided Surg 1999;4:264-74.

42. Saragaglia D, Roberts J. Navigated osteotomies around the knee in 170 patients with osteoarthritis secondary to genu varum. Orthopedics 2005;28:s1269-74.

43. Saragaglia D, Picard F, Refaie R. Navigation of the tibial plateau alone appears to be sufficient in computer-assisted unicompartmental knee arthroplasty. Int Orthop 2012;36:2479-83.

44. Koch PP, Muller D, Pisan M, et al. Radiographic accuracy in TKA with a CT-based patient-specific cutting block technique. Knee Surg Sports Traumatol Arthrosc 2013;21:2200-5.

45. Oka K, Murase T, Moritomo H, et al. Accuracy of corrective osteotomy using a custom-designed device based on a novel computer simulation system. J Orthop Sci 2011;16:85-92.

FIGURE CAPTIONS

Figure 1 Guided single-plane osteotomy. (a) Virtual K-wires are aligned to the osteotomy plane in the 3D planning application. (b) Intraoperatively, the K-wires are set according to the planning using a patient-specific guide. (c) The osteotomy is subsequently performed by guiding the saw blade along the K-wires.

Figure 2 Guided complex-plane osteotomy. (a) Virtual K-wires are aligned to the osteotomy planes in the 3D planning application. (b) The cut is coarsely defined by consecutively drilling holes using a patient-specific guide. Afterwards, the osteotomy is completed with a chisel.

Figure 3 Patient-specific reduction guide. (a) Virtual K-wires are created and fixed to the fragments. (b) The corresponding drill sleeves are integrated into a cutting guide. (c) Reduction is simulated, resulting in divergent K-wires. (d) Reduction guide consisting of two pluggable parts. (c) Reduction is completed by connecting the parts of the guide.

Figure 4 Computed tomography images of the presented cases are given before and after surgery.

Figure 5 3D computer-assisted planning and postoperative accuracy evaluation. (a) Before surgery: The pathological tibia is shown in brown and the fragment to be mobilized is outlined in red. (b) After surgery: Postoperative tibia (light blue) compared to planned reduction (green).

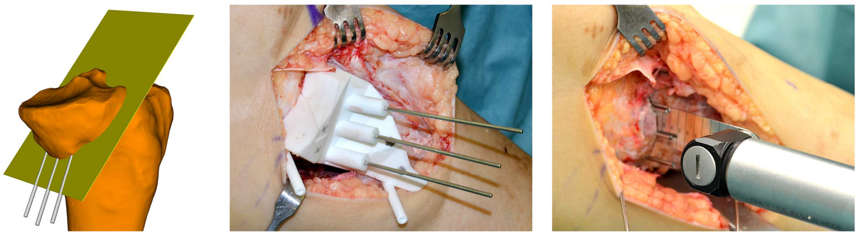
SUPPLEMENTAL DIGITAL CONTENT

Table, Supplemental Digital Content 1: Evaluation of accuracy. Pre- and postoperative difference to the 3D surgical plan with respect to translation and rotation. *Fragment only partially reduced. X, y, and z denote the axes of the coordinate system in anterior, transversal, and longitudinal direction, respectively. Rotation on x defines coronal angular deformity, rotation on y defines sagittal angular deformity, and rotation on z defines torsional deformity. Translation on x defines coronal translation, translation on y defines sagittal translation, and translation on z defines the extent of intra-articular displacement.

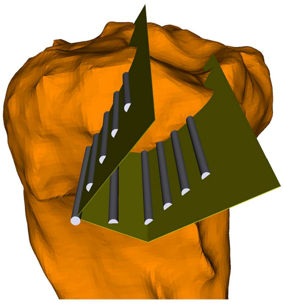
Table 1: Evaluation of accuracy.

Patient	Preoperative deformity (x,y,z)		Postoperative residual error (x,y,z)	
	Translation (mm)	Rotation (º)	Translation (mm)	Rotation (º)
1	(0.2, 4.9, 6.5)	(7.8, 2.6, 2.5)	(1.0, 0.9, 1.0)	(1.5, 0.4, 0.8)
*2	(0, 1.2, 1.3)	(2.4, 14.9, 1.8)	(0.2, 0.6, 0.2)	(3.5, 4.1, 0.3)
3	(0.2, 2.2, 3.6)	(10.0, 7.0, 12.8,)	(0.7, 1.2, 1.1)	(0.5, 1.8, 1.2)

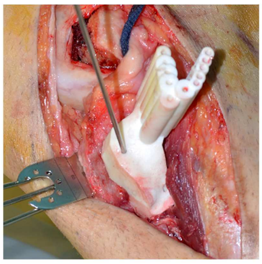
Pre- and postoperative difference to the 3D surgical plan with respect to translation and rotation. *Fragment only partially reduced. X, y, and z denote the axes of the coordinate system in anterior, transversal, and longitudinal direction, respectively. Rotation on x defines coronal angular deformity, rotation on y defines sagittal angular deformity, and rotation on z defines torsional deformity. Translation on x defines coronal translation, translation on y defines sagittal translation, and translation on z defines the extent of intra-articular displacement.



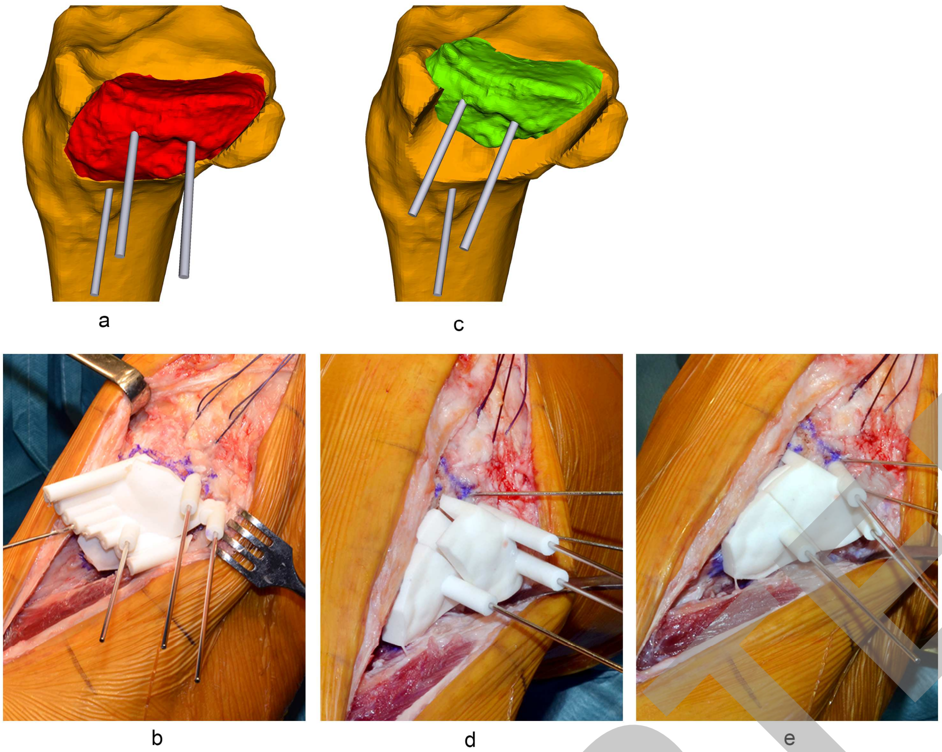
a b c



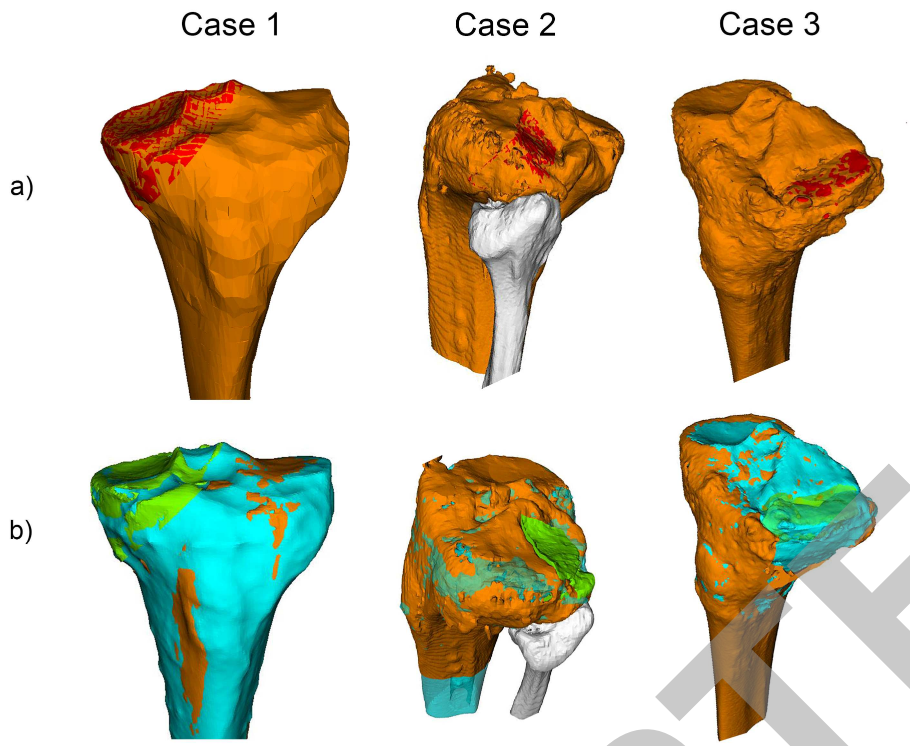
a



b


a
c
b
d
e


Case 1
Case 2
Case 3
Preoperative
AP
Sagittal
Postoperative
AP
Sagittal


Case 1
Case 2
Case 3
a)
b)